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ANALYSIS AND MODELING OF STRATOSPHERIC GRAVITY WAVE ACTIVITY ALONG ER-2 FLIGHT TRACKS

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1. INTRODUCTION

Small-scale fluctuations in winds and temperatures are routinely encountered in-flight by the Meteorological Measurement System (MMS) on NASA's instrumented ER-2 stratospheric research aircraft. Recently, Bacmeister *et al.* (1996) demonstrated that the mean along-track autospectra of these fluctuations, as compiled from over 70 long-term flights from many different geographical regions, were largely consistent with a model spectrum of gravity waves which is separable in vertical wavenumber and intrinsic frequency.

However, these stratospheric gravity-wave fluctuations also exhibit appreciable variations in intensity during many of these flight. In several cases, strong bursts of activity have been attributed to encounters with mountain lee waves which have propagated to ER-2 cruise altitudes of ~20 km (e.g., Bacmeister *et al*., 1990; Chan *et al*., 1993), while tropical flights have found bursts of activity when there was strong tropospheric convection beneath the aircraft (Alexander and Pfister, 1995).

To study mountain-wave influences on bursts of activity in ER-2 data more systematically, Bacmeister *et al*. (1994) developed an operational model for forecasting mountain-wave activity and turbulence intensities in the stratosphere. It used detailed maps of topographic elevation (5'x5' resolution) together with National Center for Environmental Prediction (NCEP) forecast winds and temperatures to predict the forcing of waves by the forecast flow over topographic ridges in any region of interest. It then used a simple hydrostatic model of mountain wave propagation and breakdown within the forecast environment to predict whether these waves propagated into the stratosphere and/or produced turbulence.

Initial tests of the model "forecasts" were made by comparing with data from ER-2 flights over undular terrain (some of which measured large velocity and temperature perturbations and concomitant turbulent buffeting of the aircraft, while others reported no significant activity). The model performed extremely well in some cases (see, e.g., Figure 2 of Bacmeister *et al.*, 1994), but for certain flights it did not predict activity when activity was measured on the ER-2, and/or *vice versa*.

Some disagreement in observed and forecast mountain wave activity is to be expected given both the uncertainties in forecast winds and temperatures, and the

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simplified two-dimensional hydrostatic theory used to force, propagate and dissipate these mountain waves.

Here, we report on recent efforts to improve the model's parameterization of wave production, propagation and breakdown, and initial comparisons between the forecasts of the improved model with an ER-2 flight in which strong wave activity and turbulence was encountered near Iceland, which the original model did not predict.

2. ADDITIONS AND IMPROVEMENTS

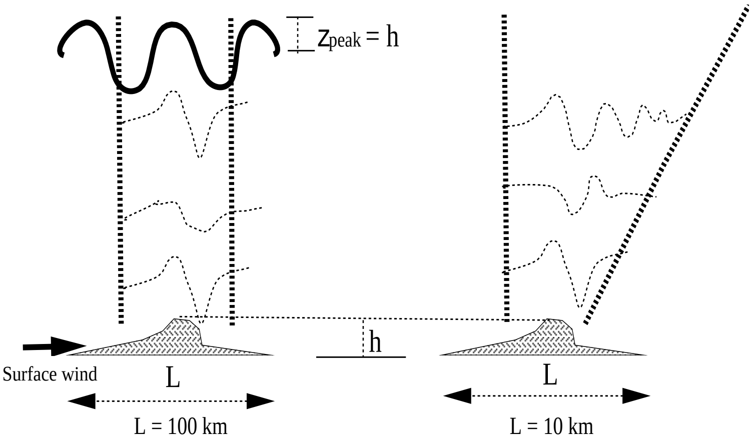

Figure 1: Schematic depiction of mountain waves forced in the model and the way their wavelengths and amplitudes are assigned.

The main change to the original model of Bacmeister *et al.* (1994) was to replace the two-dimensional hydrostatic wave model with a four dimensional nonhydrostatic ray-tracing model of wave propagation, refraction and amplitude evolution. The model used is the so-called Gravity-wave Regional Or Global Ray Tracer (GROGRAT), originally described by Marks and Eckermann (1995), but upgraded significantly since then, as reported by Eckermann and Marks (1996). The model simulates ray paths of nonhydrostatic gravity waves propagating through arbitrary atmospheric environments which can vary in all three spatial dimensions as well as temporally. Wave amplitudes along the ray path are computed using wave action conservation principles, and damping due to wave saturation (either convective or dynamical), infra-red radiation by CO_2 and O_3, and background turbulence are all included. These damping processes give rise to wave-induced turbulence along the ray which we use in the improved forecast model.

Inclusion of GROGRAT also required improvements to the parameterization of waves emanating from ridges. This is because the two-dimensional hydrostatic wave theory did not need to specify horizontal wavelengths of mountain waves to compute propagation and amplitude of these waves, and so they were never assigned. Figure 1 shows the new scheme that we have used in this study. For a total ridge width of L, we currently set the horizontal wavenumber $K_{tot} = 4\pi/L$, which accounts for the fact that most of the ridge elevation h (which forces the wave) is contained in the central $L/2$ region of the ridge. More sophisticated parameterizations are planned, but this gives a reasonable first-order estimate of mountain wave horizontal wavelengths.

3. RESULTS

Figure 2 shows data from the ER-2 flight of 10th. February 1989, when the plane flew from Stavanger, Norway to the south-east of Greenland, then returned.

Strong vertical velocity activity (which is superimposed upon the flight path in Figure 2) was encountered over open ocean as the aircraft passed to the north-east of Iceland. It seemed likely that mountain waves from orography on Iceland produced this activity. However, the model of Bacmeister et al. (1994) did not forecast it, since the hydrostatic wave equations always simulate purely vertical propagation above the mountain, as shown on the left of Figure 1, whereas the activity in Figure 2 does not occur directly over Iceland. Nonhydrostatic effects, however, can produce downstream advection of mountain wave activity, as shown on the right of Figure 1. Since winds over Iceland were from the south-west on this day, such nonhydrostatic downstream dispersion could possibly explain the observed activity on this day.

Figure 3 shows the forecast ray paths for that day, using the improved ray model of mountain wave propagation. We see that mountain wave ray paths now intersect the flight track in the regions where strong activity was observed. Thus the ray model has clearly improved the performance of the forecast in this case. Further work on model improvements and further comparisons with ER-2 data are planned.

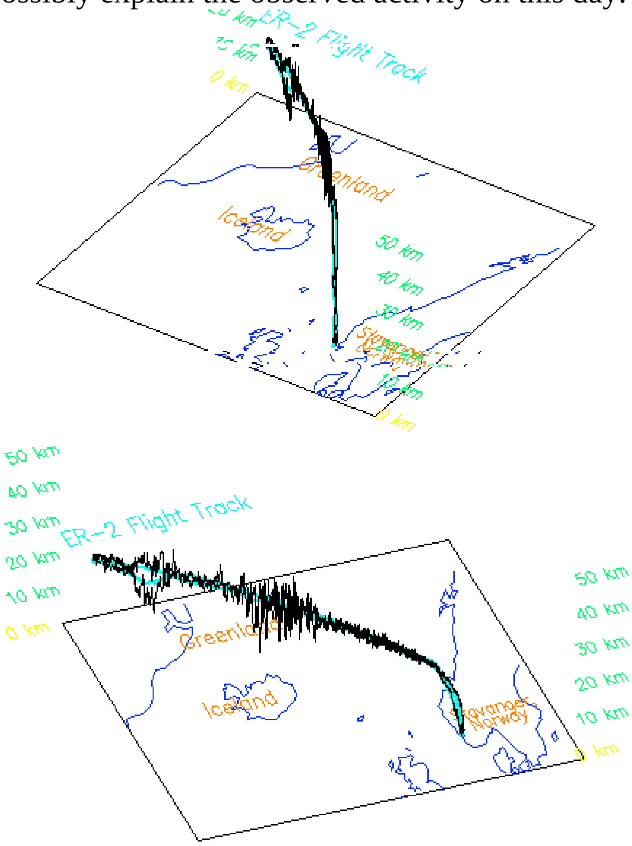

Figure 2: Views at two different azimuths of the vertical velocity activity recorded along the ER-2 flight path on 10 February 1989.

Further details on the original and improved forecast model, the GROGRAT model, and the results of our continuing simulations in this area can be found by accessing the NRL Dynamics Group home page, which is at http://uap-www.nrl.navy.mil/dynamics/html/dynamics.html. Animations of the results in Figures 2 and 3 through a full 360^{o} in azimuth can also be found there.

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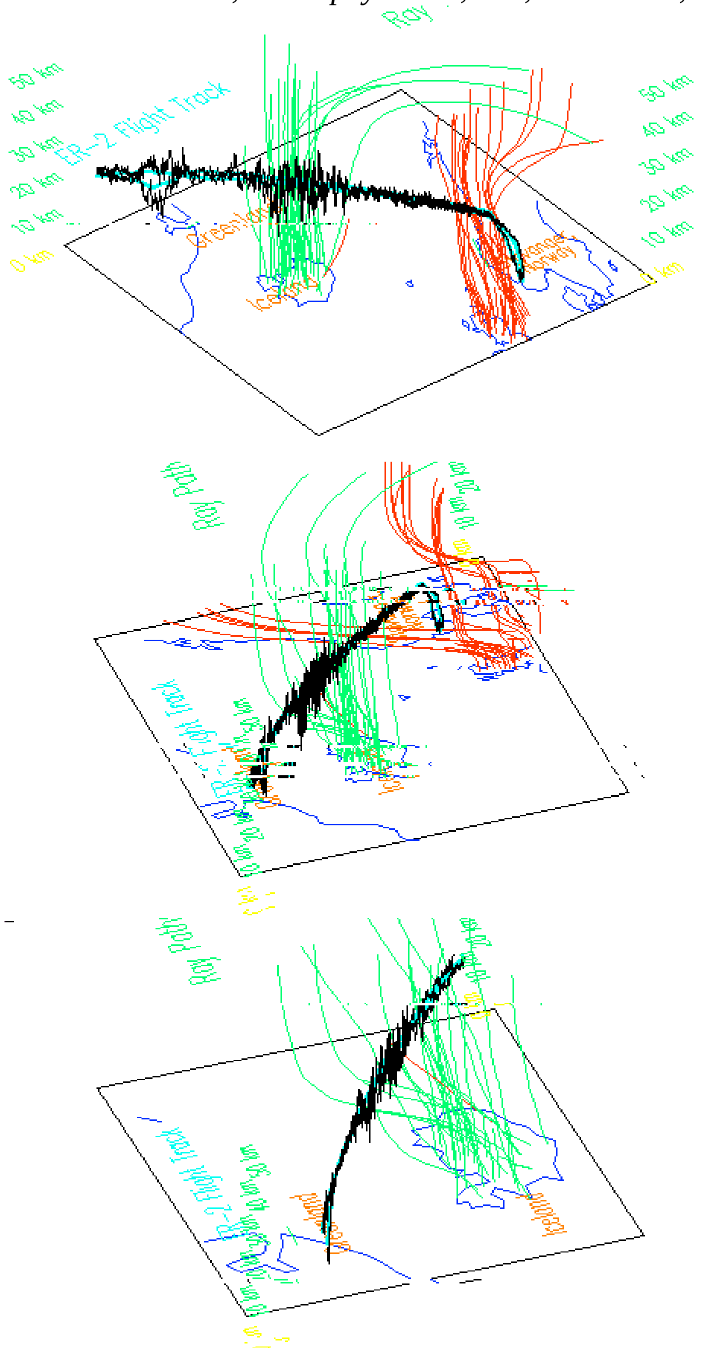

Figure 3: Forecast Ray Paths for 10 February 1989. The bottom plots zooms into the area near Iceland.